QGPs, The Early Universe, and the Hunt for Particles Beyond the Standard Model

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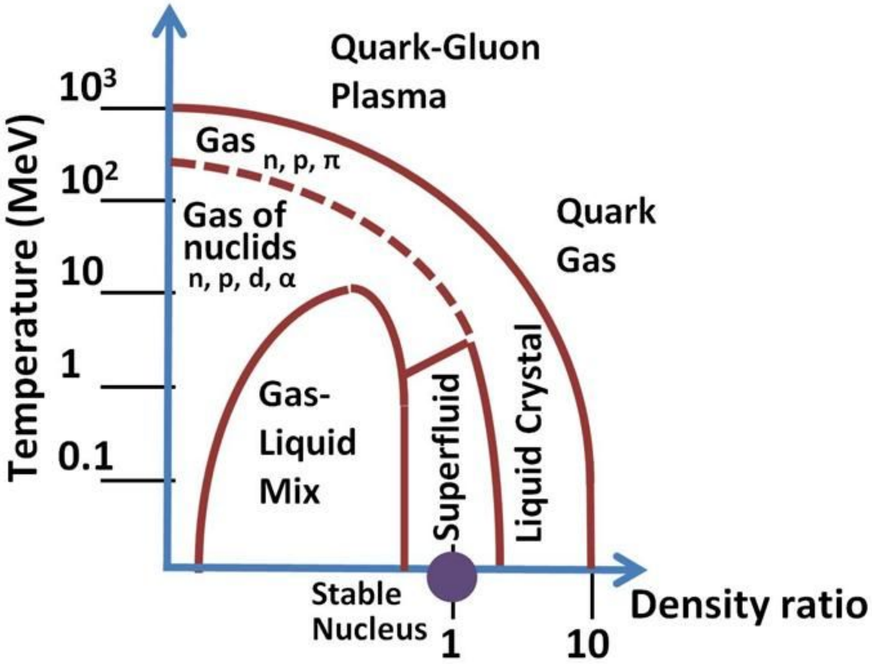
What is a QGP?

- State of matter at extremely high temperatures and density of particles ~100 MeV (10^{12}K)
- Asymptotically free strong-interacting quarks and gluons, which are ordinarily confined by color confinement inside atomic nuclei or other hadrons. Hence μ → 0 as the energy scale increases
- Quarks interact weakly at high energies, allowing perturbative calculations (perturbative lattice QCD). At low energies the interaction becomes strong, leading to the confinement of quarks and gluons within composite hadrons.



Mathematical Background

A QGP can be approximated as a relativistic free gas with μ = 0

Number density, and subsequently energy density, can then described by the quantum distribution function:

$$\epsilon_i = \int \frac{d^3 p_i}{(2\pi)^3} \frac{E_i}{e^{\beta E_i} \pm 1} \quad \begin{aligned} &= \frac{\pi^2 (k_B T)^4}{30} \quad \text{(for bosons)} \\ &= \frac{7}{8} \frac{\pi^2 (k_B T)^4}{30} \quad \text{(for fermions)} \end{aligned}$$

$$\epsilon = \sum_{i=1} g_i \epsilon_i = g_* \frac{\pi^2 (k_B T)^4}{30}$$

Where g_* is the total degeneracy of bosons and fermions (weighted by ⅞ fermions)

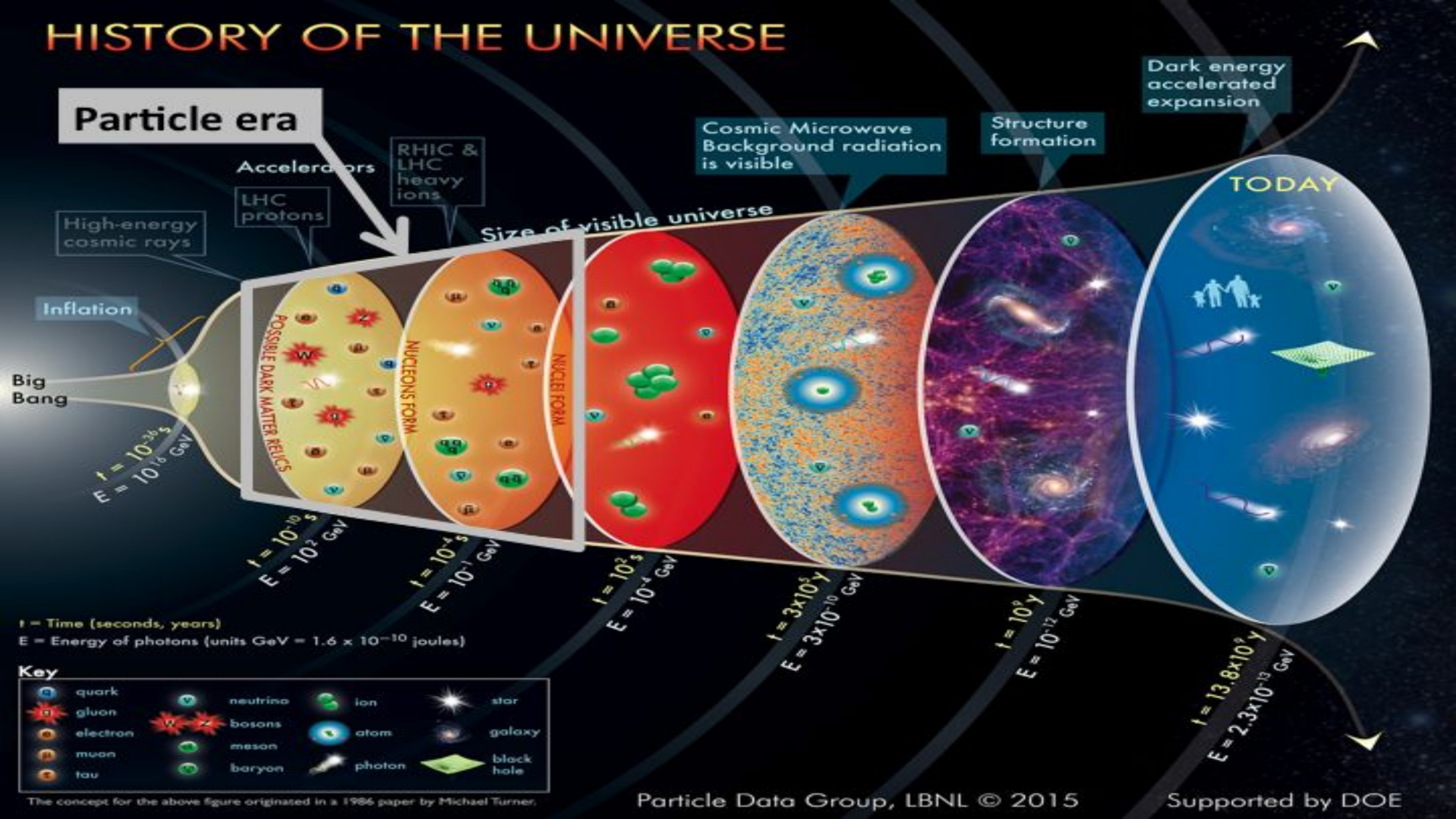
Total Degeneracy of a QGP

This system is dominated by the strongly interacting DFs, so to a good approximation we can regard it as a system of only quarks and gluons

Gluons: (2 helicities)x(8 color combinations) = 16

Quarks: (3 colors)x(2 spins)x(2 charges)x(3 flavors) = 36

$$g_* = g_b + \frac{7}{8} g_f = 47.5$$


HISTORY OF THE UNIVERSE
Particle era
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Big Bang
Size of visible universe
Cosmic Microwave Background radiation is visible
Structure formation
Dark energy accelerated expansion
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
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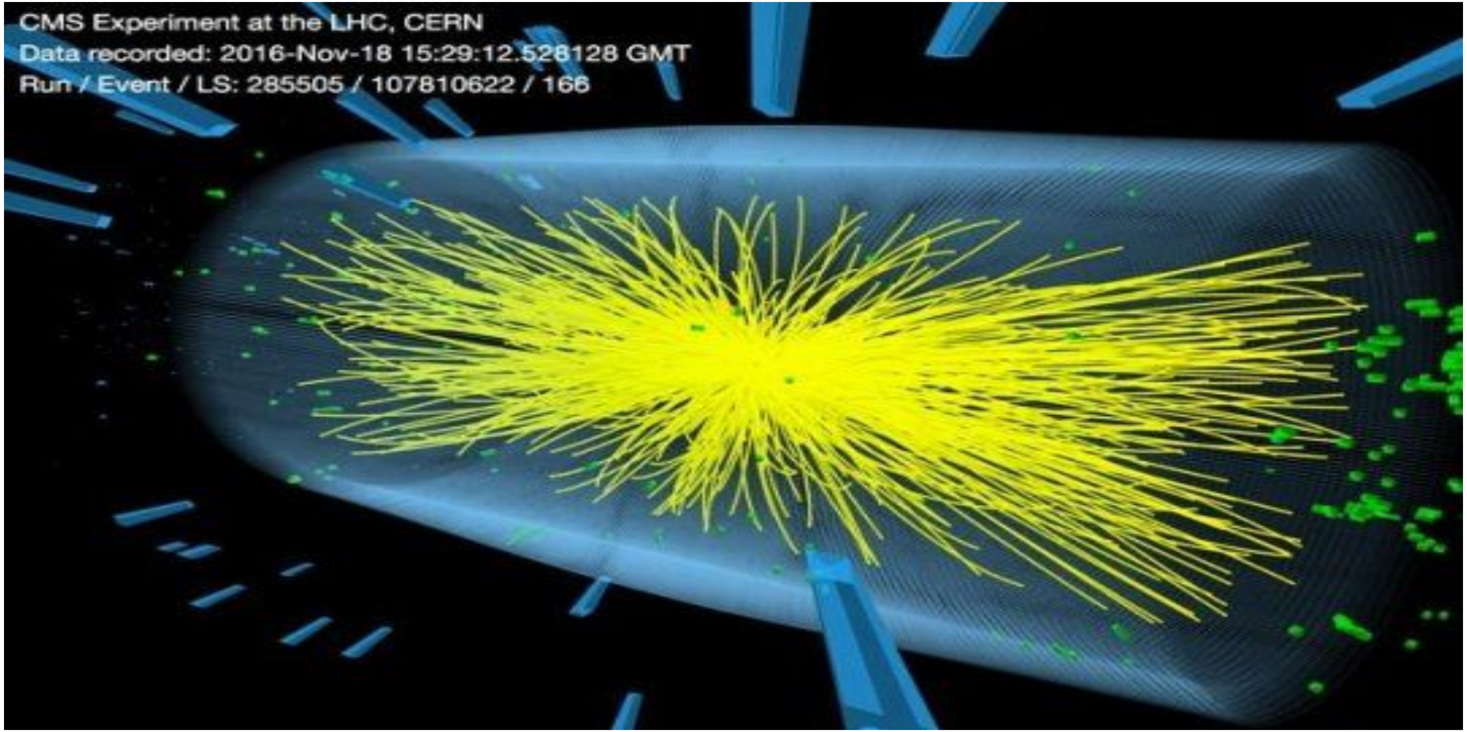
The Quark Epoch

Between 10^{-12} seconds and 10^{-6} seconds after the Big Bang

The forces of the Standard Model have separated, but energies are too high for quarks to coalesce into hadrons, instead forming a quark-gluon plasma. These are the highest energies directly observable in experiment in the Large Hadron Collider.

Experiments such as ATLAS and CMS in the LHC recreate energy scales for a QGP. By studying these collisions we can learn about these energy scales



[1]

Experiments

- Collisions of lead or other similarly massive ions, such as gold nuclei in the LHC form the hot, dense medium (QGP). In these heavy-ion collisions the hundreds of protons and neutrons in two such nuclei smash into one another at energies of upwards of a few TeV each. This forms a miniscule fireball in which everything “melts” into a quark-gluon plasma.

- The quarks and gluons fragment into highly collimated “jets” of particles that in turn lose energy through “jet quenching”.

- The fireball cools in roughly 10^{-32}s [3], and the individual quarks and gluons recombine into ordinary matter. The debris contains particles such as pions and kaons, protons and neutrons, antiprotons and antineutrons, which may combine to form the nuclei of antiatoms as heavy as helium.

Hunt for BSM Physics

Discrepancy with Observation:

[2] $$n_B = g_B \left(\frac{M_p T}{2\pi}\right)^{3/2} e^{-\frac{M_p}{T}} \qquad n_\gamma \simeq \frac{2}{\pi^2} T^3$$

$$\begin{aligned} \frac{n_B}{n_\gamma} &\sim g_B \left(\frac{M_p}{T}\right)^{3/2} e^{-\frac{M_p}{T}} \\ &\sim 10^{-19} \quad (@T = 20 \text{ MeV}) \end{aligned}$$

We would expect the chance excess of baryons over antibaryons to be a very small fraction of the total number of both. Therefore, the observed $6{\times}10^{-10}$ fraction of baryons relative to the number of photons is not possible to generate by just a statistical fluctuation.

Why is there so much matter in the universe?

Baryogenesis - models for baryonic asymmetry

Conclusion

- Understanding how QGP behave lends insight into the very beginnings of our universe

- Predicting how these systems behave allow us to probe concepts and test theories relating to fundamental high energy physics

- Discrepancies between what we know about QGPs and what we observe macroscopically in the cosmos can help guide us on where to look. Beyond the standard model, what do these predictions not account for (baryon asymmetry, where does dark matter fit into this)

Sources

1. Measurement of the fragmentation function for photon-tagged jets in 5.02 TeV Pb+Pb and pp collisions with the ATLAS detector (ATLAS-CONF-2017-074).
2. A Modern Introduction to Nuclear Physics by Prof. Xiangdong Ji
3. Measurements of the Nuclear Modification Factor for Jets in Pb+Pb Collisions at 2.76 TeV with the ATLAS detector (Phys. Rev. Lett. 114 (2015) 072302, see figures).
4. Measurement of jet p_T correlations in Pb+Pb and pp collisions at 2.76 TeV with the ATLAS detector(arXiv: 1706.09363, see figures).
5. Study of photon-jet momentum correlations in Pb+Pb and pp collisions at 5.02 TeV with ATLAS(ATLAS-CONF-2016-110).
6. See also the full lists of ATLAS Conference Notes and ATLAS Physics Papers.